

Experimental study of the potential of eucalyptus fibres for evaporative cooling



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ABSTRACT

Energy consumption by human enhanced activities has led to distinctive environmental problems; in particular, climate change and global warming. In hot regions, the main reason for energy consumption comes from the cooling of many buildings. The intensity and duration of the sunshine in hot regions have a direct relation with the usage of cooling systems. The aim of this paper is to study the performance of eucalyptus fibre pads which can be used as a new material for the evaporative cooling process in order to reduce the energy consumption caused by cooling loads. A wind tunnel is used to investigate the performance of evaporative cooling by eucalyptus fibres. This paper also analyses the behaviour of the eucalyptus fibres under different conditions. From the measurement of one material sample, it was found that the maximum reduction of air temperature was between 11.3 °C and 6.6 °C, while the maximum cooling efficiency was in the range of 71% and 49% at 0.1 and 0.6 m/s air velocities respectively. Corresponding cooling capacities were also calculated as 108 W and 409 W indicating a directly proportional relation between air velocity and cooling performance.

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1. Introduction

Evaporative cooling is one of the sustainable cooling methods that can reduce the building interior air temperature. This method has been used since pre-scientific eras in very hot regions. The Egyptian architect, Hassan Fathy (1900–1989) placed porous clay and pottery jars filled with water in front of windows to create cool ventilation when air flows around the jars (Fig. 1). The porosity of the clay allows the surface to remain wet and the air is cooled by evaporation.

Since the air coming from outside is in direct contact with water in the jar, this is called direct evaporative cooling [2–5]. Material used in the direct evaporative cooling method has been widely investigated by many researchers for hot climate conditions. According to the previous studies, these materials can be ceramic, plastic and paper which show good performance in reducing temperature as it is shown in Table 1. Different fibre pads are also

used as a cooling pads such as jute fibres [6], coconut fibres [7], luffa fibre [8] and rice husk [9].

Jain and Hindoliya [10] conducted studies using Palash Fibre which provided a 14 °C temperature difference. Celdek, straw and sliced wood pads were tested for greenhouses for optimizing greenhouse temperature and humidity for crop growth. The results revealed that sliced wood pads showed better performance compared to other evaporative cooling materials [11]. Wanphen and Nagano [12] have found that siliceous shale absorbs more vapour due to the higher pore volume and pore size, which provided 6.8–8.6 °C temperature differences. Gunhan et al. [13] studied the potential of pumice stones, volcanic tuff and greenhouse shading net at four different levels of air velocity and two different levels of relative humidity (RH). As a result, it was obtained that volcanic tuff pads perform best at 0.6 m/s air velocity. Atikol and Hacısevki [14] have studied the suitability of evaporative cooling systems in Cyprus, particularly in Nicosia. According to their feasibility study, it is suggested that evaporative cooling can be used in May and September without any need of an additional cooling system. It was also found that in June effective cooling can be achieved only between 12.00 p.m. and 15.00 p.m. hours. Since the evaporative cooling is not sufficient in July and August, an

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Nomenclature

A_c	cross section area, m^2
c_p	= specific heat at constant pressure, $kJ/kg^\circ C$
c_{pda}	specific heat of dry air, $kJ/kg^\circ C$
c_{pww}	specific heat of water vapour, $kJ/kg^\circ C$
COP_s	system coefficient of performance
h	enthalpy, (kJ/kg)
h_k	specific enthalpy of humid air, (kJ/kg)
h_1	specific enthalpy of inlet air, (kJ/kg)
h_2	specific enthalpy of outlet air, (kJ/kg)
l_{ho}	heat of evaporation of water, kJ/kg
\dot{m}_a	mass flow rate of air, kg/s
m_w	evaporation rate, kg_{ww}/s
Q_c	sensible cooling capacity, kW
T	temperature, $^\circ C$
T_1	inlet temperature, $^\circ C$
T_2	outlet temperature, $^\circ C$
T'_1	inlet wet bulb temperature, $^\circ C$
V	velocity of air, m/s

W_p	pump electric power, kW
w	absolute humidity of air, kg_{ww}/kg_{da}
w_2	outlet absolute humidity, kg_{ww}/kg_{da}
w_1	inlet absolute humidity, kg_{ww}/kg_{da}

Abbreviations

ASHRAE	American society for Heating Ventilation Refrigeration and Air conditioning Engineer
CC	cooling capacity, kW
COP	coefficient of performance
DBT	dry bulb temperature, $^\circ C$
RH	relative humidity, %
SCC	specific cooling capacity, kWh/kg
ER	evaporation rate, gr/s
WBT	wet bulb temperature, $^\circ C$

Greek symbols

ΔT	temperature difference, $^\circ C$
η_ζ	cooling efficiency, %
ρ	density of air, kg/m^3

auxiliary cooling system is needed during that period.

The humidity content (absolute humidity) of ambient air could directly affect the performance of an evaporative cooling system. When the ambient humidity is increased, the cooling efficiency becomes lower due to the limitations in the amount of vapour that could be added to the air. In order to increase the evaporative cooling performance in humid condition, desiccant materials can be used to reduce the air humidity level [20,21]. This is called desiccant enhanced evaporative cooling. Rafique et al. [22] developed a mathematical model for solid desiccant cooling system under humid conditions of Dhahran, Saudi Arabia. It was found that this system can be applied to provide cooling demands for Dhahran. Banik and Ganguly [23] developed a desiccant assisted distributed fan-pad ventilated greenhouse system for the cultivation of varieties of Gerbera for the plains of Gangetic Bengal in Indian sub-continent. It was found that the outlet temperature drops below $27^\circ C$ with the use of desiccant, while it was nearly $29^\circ C$ without using the desiccant.

In present research, temperature reduction between inlet and outlet air through eucalyptus fibres is investigated as a factor for evaporative cooling performance. Besides cooling capacity and COP for eucalyptus fibres were analysed for better understanding of the material's performance. Thermodynamic analysis and process optimization were also conducted to improve the efficiency of eucalyptus fibre based evaporative cooling system by the use of different inlet temperatures and air velocities during the testing.

During the selection of pad materials for evaporative cooling technology, the factors such as saturation efficiency, availability, cost, application and environment should be considered [12]. When the local, light in weight and cheap evaporative cooling pad, eucalyptus fibres, compared with the commercial pads such as celdek pad, cellulosic pad, aspen pad, rigid medium pad etc., commercial pads have good saturation efficiency, however, they are more expensive compared to local materials due to their preparation, material and fabrication processing costs [24–28]. Commercial pads are specially manufactured however, since these pads are more expensive than local materials, they are not suitable for low income countries [27]. Therefore eucalyptus fibres which is locally available, cheap and easily constructed material, is essential for using in evaporative cooling technology. Considering the cost of celdek, it is \$ 110 in the market [24,27] which is more expensive

than aspen [29]. Although the cost of aspen in the market is \$ 3.98–\$ 4.98 [30], there is a potential to increase the growth of algae which causes rotting and thus, blocking the air flow through the pad [29].

In addition to these, cellulose paper is also widely used as a pad material for evaporative cooling process however, these pads deteriorate and need to be changed regularly due to the reduced water absorption capacity and using of low quality of water [31]. Since the mineral or dust are produced on the surface, these pads cannot longer absorb water for the process. In the market, the cost of the cellulose pad is \$ 88 – \$ 129 [30]. On the other hand, since eucalyptus fibres is locally available and cheap, the material can be changed regularly.

Warke et al. [26] studied the performance of cellulose pad with 50 mm thickness. It was found that the cooling efficiency is 61.19% at 1.6 m/s air velocity. As seen in Table 1, Dagtekin et al. [18] found the cooling efficiency in between 75% and 85%. Whereas, the cooling efficiency of eucalyptus fibres was found as 71% with 20 mm thickness.

Galvanized metal sheet is also used with commercial pads (i.e. cellulose-based pad) however, besides of being expensive, it also becomes heavy in weight which gives additional load to the system. It also corrodes with time causing not longer life span [28]. Since the eucalyptus fibres is lighter than the metal, it does not apply any additional load to the system. Considering the limited life span and high costs of commercial pads, also the energy and material consumption for their production, there is a need to develop low cost, natural and environmentally friendly materials to be replaced with the currently used commercial pads.

The objectives of this paper are to gather information about the cooling efficiency and cooling capacity for evaporative cooling of eucalyptus fibres and to analyse the effect of air temperature and air velocity on the material performance. Since this natural material is easy to obtain, low cost, natural and sustainable, it represents a great potential to be used as evaporative cooling pad. It is also worth mentioning that this material has not been investigated before for evaporative cooling.

This study aims to promote and disseminate knowledge on a sustainable air conditioning method that uses a novel organic and environmentally friendly material; eucalyptus fibres. Thereby performed research provides an alternative energy solution to currently used vapour compression system, which has high

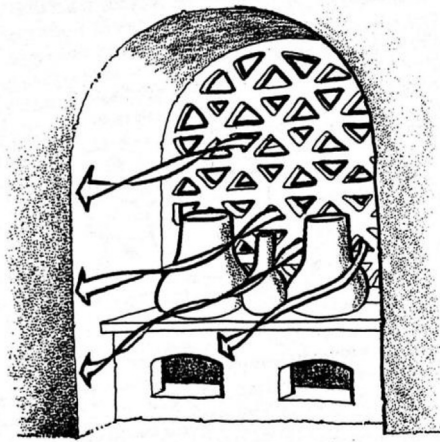


Fig. 1. Air flows around jars creating cool breeze [1].

operational costs and which uses environmentally harmful refrigerants. In this context, presented work delivers new insights on a renewable and sustainable cooling material/core through experimental investigations, thereby the content of the study falls within the scope of the Renewable Energy Journal.

2. Materials and methods

2.1. Wind tunnel system

An Open Wind Tunnel (HM170) was used as the rig for laboratory testing of eucalyptus fibre based evaporative cooler performance under controlled environmental conditions. The dimensions of the tunnel are $2870 \times 890 \times 1540$ mm and the flow cross section area is 292×292 mm as shown in Fig. 2. In the air blower section, the inlet air was heated with a 2 kW heater in order to increase the air temperature to the set point.

Dry and wet bulb temperatures and relative humidity were controlled during the experiment in order to provide steady environmental conditions. Uniform air flow was provided by the honeycomb structure which is located at the entrance of the duct.

2.2. Materials and instrumentations

In this study, eucalyptus fibre was used as an evaporative cooling material. It is native to Australia and some Pacific regions. As eucalyptus tree grows fast, it could be utilized in many industries for timber, firewood, pulp, charcoal ... etc. production [32]. According to Couppis [33], eucalyptus grows to a diameter of 6 feet (1.82 m) within 40 years. However, it can drain a huge amount of water from underground. Since eucalyptus consists of hemi-celluloses inside, it has a flexible structure. Accordingly, this can be

used for the production of absorbent paper; in particular toilet paper and tissue [34]. Considering the effective water absorption and high water holding capacity of eucalyptus fibre, it is proposed to investigate its feasibility for evaporative cooling applications within this study.

For the experimental study, eucalyptus fibres were collected from the barks of the eucalyptus tree. They were soaked into the water in order to create thin fibres easily. The fibres were then separated and embedded into a $28 \times 28 \times 2$ cm mesh wire frame (Fig. 3). In order to keep meshed fibres wet during the experimentation, a water dripping was provided with an 18 mm water pipe which has been placed on top of the meshed structure. A 20 W water pump was also used to provide water circulation between the water tank and pipeline. When water from the pipe was dripped onto the material, the excess water was collected in the water tank and reused in the system in order to minimize water consumption. The preparation stages of the meshed eucalyptus fibres is illustrated in Fig. 3.

The instruments such as datalogger and anemometer were provided by the University of Nottingham. A DT500 model data taker which was connected to a computer was used to record the air temperatures, wet bulb temperatures (WBT) and surface temperatures of the material continuously. K-type thermocouples, which were connected to the datalogger, were used to record data of the inlet and outlet measurements. An anemometer was used to measure the inlet and outlet air velocity which was controlled during the test. The microclimate probe and pocket weather meter were used to measure the relative humidity and wet bulb temperature. The sensors used in the experiments are listed in Table 2.

It is necessary to find the experimental error of the measured values during experimentations. Uncertainty analysis could be performed by the use of the propagation of error formula [35,36]. By this method, the source of errors, which are the variables used in experimental analysis (i.e. temperature difference, cooling efficiency, relative humidity ... etc.) are identified. The experimental uncertainty can be obtained by the Eq. (1):

$$Y = f(X_1, X_2, \dots, X_n)$$

$$\delta Y = \sqrt{\left(\frac{\partial Y}{\partial X_1} \delta X_1\right)^2 + \left(\frac{\partial Y}{\partial X_2} \delta X_2\right)^2 + \dots + \left(\frac{\partial Y}{\partial X_n} \delta X_n\right)^2} \quad (1)$$

where δY is the overall uncertainty in the result. (X_1, X_2, \dots, X_n) are the set of measurement which are directly measurable parameters. $\delta X_1, \delta X_2, \dots, \delta X_n$ are the overall uncertainty of parameters. Each term represents the same calculation: The partial derivative of Y with respect to X_1 is multiplied by the uncertainty value for that variable.

According to the uncertainty range for each instruments shown in Table 2, the overall uncertainty results for each measured variables are seen in Table 3. The largest error occurred in relative humidity.

Table 1
Previous studies on evaporative cooling material.

Researcher	Material	ΔT (°C)	Air Velocity (m/s)	Cooling efficiency (%)
Sulaiman [15]	Jute	—	—	62
Liao, Chiu [16]	Coarse Fabric PVC Sponge	—	1.0–1.5	63–86
Wanphen et al. [12]	Siliceous Shale	6.8–8.6	—	—
He et al. [17]	Porous Ceramic	2–4	1–3	—
Jain et al. [10]	Palash Fibre	13.94	—	81–84
Dagtekin et al. [18]	Cellulose based pad	4–7	0.5–1.5	75–85
Shrivastava et al. [19]	Coconut coir	13	—	60

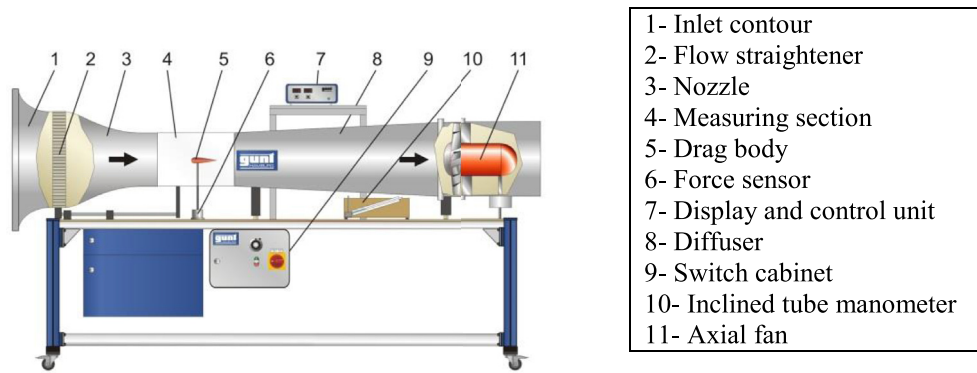


Fig. 2. Schematic of the open wind tunnel (HM170).



Fig. 3. The process of wiring eucalyptus fibres.

Table 2
Characteristics of experimental sensors.

Sensor type	Sensor model	Sensor accuracy	Specification range
Temperature	Type-K Thermocouple	$\pm 1.5^{\circ}\text{C}$	$-50 \sim +250^{\circ}\text{C}$
Relative humidity	Kestrel 4000 weather meter	$\pm 3\%$	5–95%
WBT	Kestrel 4000 weather meter	$\pm 2^{\circ}\text{C}$	$-29 \sim 70^{\circ}\text{C}$
Air flow	Testo 405 V1 anemometer	$\pm 5\% \pm 0.1 \text{ m/s}$	0–10 m/s
Relative humidity	Metrel 6201 multinorm	$\pm 2\%$	0–60%
Temperature	Metrel 6201 multinorm	$\pm 0.2^{\circ}\text{C}$	$20 \sim 60^{\circ}\text{C}$
Water temperature	Multi-thermometer	$\pm 1^{\circ}\text{C}$	$-50 \sim +300^{\circ}\text{C}$

Table 3
Errors for uncertainty analysis.

Variable	Temperature difference ($^{\circ}\text{C}$)	Cooling efficiency (%)	Relative humidity (%)
Error	1.3%	7.1%	8.3%

2.3. Experimental procedures and methodology

The performance of the material was studied by setting the inlet air temperature to around $35\text{--}36^{\circ}\text{C}$. For measuring the temperatures, thermocouples were placed in the outlet and inlet sections with the same distance from the material to measure the dry bulb temperature (DBT) and wet bulb temperature (WBT) of the air. Figs. 4 and 5 show the schematic diagram and view of the experimental testing rig. The moistened cotton was wrapped around the thermocouples to record the WBT of the aforementioned positions. RH was also measured by a microclimate probe for both sides of the material. Eventually, the results were checked in the psychrometric chart. The 2 kW heater was positioned in front of the blower in order to keep the inlet air temperature constant at the set point ($35\text{--}36^{\circ}\text{C}$). The inlet RH was also kept at $\sim 20\%$ during the

experimental testing.

The data recording has begun after 30 min of the start of the experiment to ensure that the system is operating under steady state conditions. The measurements were recorded once in every minute and totally 240 readings were recorded over four hours testing duration.

In regards to the cooling efficiency of an evaporative cooling system, the air flow rate is a key parameter, significantly influencing the system performance. Therefore, air velocity was chosen as the variable during the tests to ascertain its impact on the cooling effectiveness obtained with the eucalyptus fibres. Accordingly, air velocity was set to 0.1, 0.3, 0.6, 0.9 and 1.2 m/s to compare the evaporative cooling performance of the system at different air velocities.

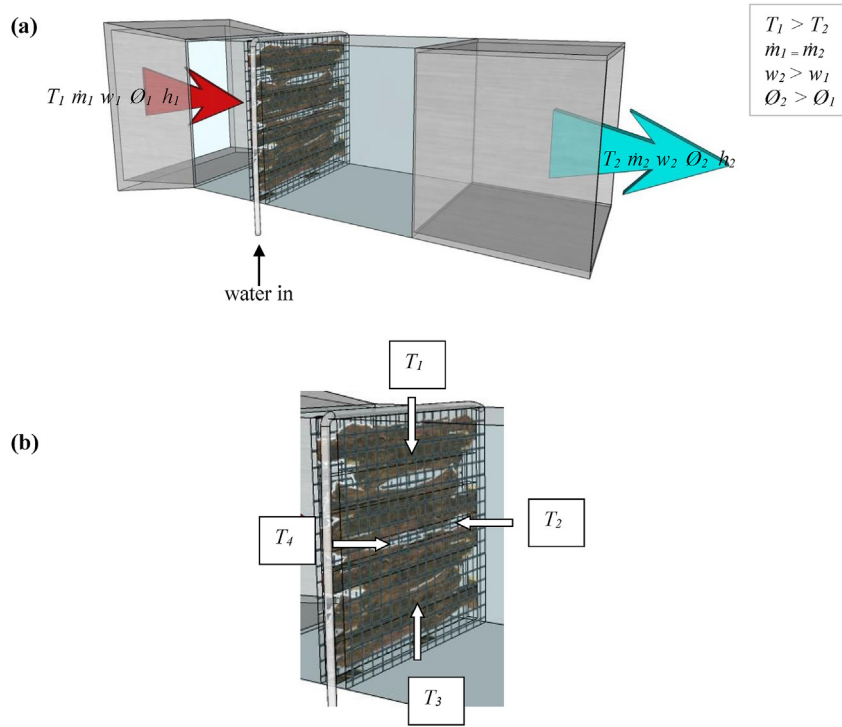


Fig. 4. (a) Schematic diagram of the experimental testing rig and (b) thermocouple locations.

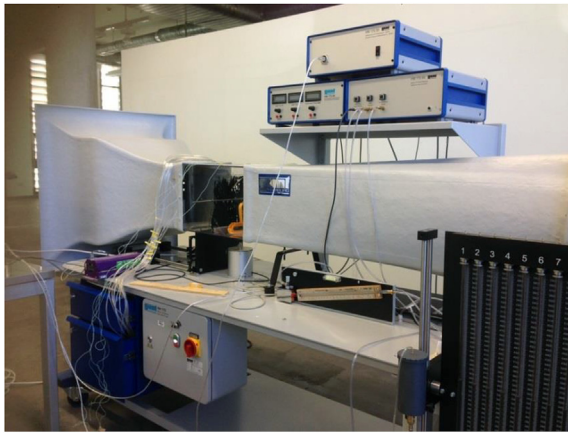


Fig. 5. General view of the experimental testing rig.

2.4. Calculations for performance analysis

The performance of eucalyptus fibres was evaluated according to the following equations:

The temperature difference between the inlet and outlet air is a common factor for evaluating the material performance as given in the following expression:

$$\Delta T = T_1 - T_2 \quad (2)$$

The cooling efficiency (saturation effectiveness) of eucalyptus is calculated with Eq. (3) given by ASHRAE (2001) [37]:

$$\eta_s = \frac{(T_1 - T_2)}{(T_1 - T'_1)} \times 100 \quad (3)$$

where T_1 is the dry bulb temperature of inlet air, T_2 is the dry bulb

temperature of outlet air and T'_1 is the wet bulb temperature of inlet air. From the equation, the efficiency of an evaporative cooling system could be calculated as the ratio of the difference between inlet -outlet DBT and difference between inlet DBT - outlet WBT. The temperature levels of inlet air for testing in the laboratory were regulated according to the temperature of the days in summer when cooling is most needed.

The mass flow rate of air through the material is calculated by density, ρ , and velocity, V , of the air, and cross section area, A_c , of material sample which is defined as:

$$\dot{m}_a = \rho V A_c \quad (4)$$

The sensible cooling capacity is an important parameter for performance analysis as given by:

$$Q_c = \dot{m}_a C_p (T_1 - T_2) \quad (5)$$

where, \dot{m}_a is the mass flow rate and C_p is the specific heat capacity of air.

The enthalpy of humid air is written by the following equation:

$$h_k = 1.006t + w(2501 + 1.85t) \quad (6)$$

where t is the temperature in $^{\circ}\text{C}$, w is the absolute humidity of air in $\text{kg}_{\text{wv}}/\text{kg}_{\text{da}}$. The specific heat of dry air (c_{pda}) is $1.006 \text{ kJ/kg}^{\circ}\text{C}$ and the specific heat of water vapour (c_p) is $1.85 \text{ kJ/kg}^{\circ}\text{C}$, when the temperature range is between -10°C and 40°C . The heat of evaporation of water (h_{ho}) is 2501 kJ/kg .

Absolute humidity, w , can be defined as the mass of water vapour per kg dry air, which could be calculated with the following equation [38]:

$$w = 216.7 \times \frac{\frac{RH}{100\%} \times 6.112 \times \exp\left(\frac{17.62 \times T}{243.12 + T}\right)}{273.15^{\circ}\text{C} + T} \quad (7)$$

The performance analysis was also carried out using the

coefficient of performance (COP), which is the ratio of the cooling capacity, Q_c , to electric input power, which is the total of pump (W_p) and fan (W_f) work.

$$COP = \frac{Q_c}{W_p + W_f} \quad (8)$$

Evaporation rate is calculated with the Eq. (9) to ascertain the amount of water required for the system. Absolute humidity can be determined through the psychrometric chart by plotting the intersection point of DBT and RH of air. It is defined as the water vapour content per kg of air flow at the inlet, w_2 , and at the outlet, w_1 :

$$m_w = \dot{m}_a (w_2 - w_1) \quad (9)$$

The specific cooling capacity (SCC) is determined to find the amount of cooling capacity obtained per kg of water evaporated. It is the ratio of cooling capacity (CC) to evaporation rate (ER) and defined with the Equation (10):

$$SCC = \frac{CC}{ER} \quad (10)$$

3. Results and discussion

The evaluation of the cooling performance was performed based on two important parameters such as inlet DBT and air velocity. In this context, the experimentations were repeated by varying these parameters. The temperature differences, cooling efficiency, mass flow rate, cooling capacity, evaporation rate, COP and SCC of the eucalyptus fibres were measured and calculated based on the temperature and RH readings during the experiments.

3.1. The effect of air velocity on temperature and relative humidity difference

The outlet temperature at different air velocities are shown in Fig. 6. It is obvious that at 0.1 m/s speed, the temperature difference was higher compared to higher air velocities. This is because that the more time the air is exposed to material at lower air velocity, the more water is evaporated. Therefore, more temperature reduction is achieved. Besides, as the mass flow rate of air is less at low air velocities more temperature drop is obtained for the same rate of cooling capacity. According to the testing results, the average

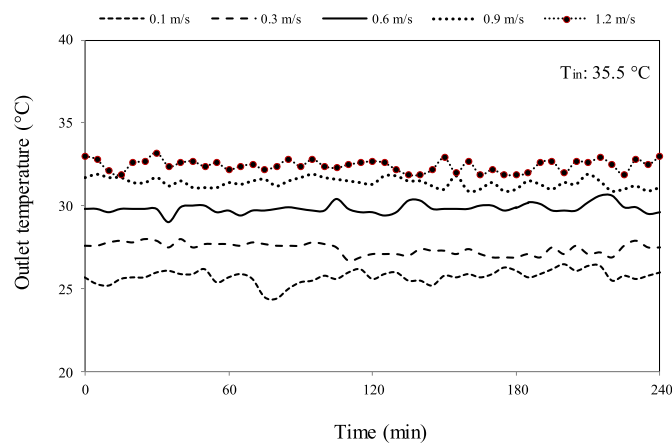


Fig. 6. Effect of air velocity on outlet temperature.

temperature drop of air at 0.1 m/s, 0.3 m/s, 0.6 m/s, 0.9 m/s and 1.2 m/s air velocities were 9.8 °C, 8.1 °C, 5.7 °C, 4.1 °C and 3.1 °C respectively. In Fig. 7, the correlation between outlet dry bulb temperature and air velocity is shown. The trend line supports the data given in the graph. As seen, temperature difference is indirectly proportional with the increased air velocity.

Consequently, eucalyptus fibres showed a better performance at low air velocity operating conditions in terms of providing higher ΔT . However in order to determine the overall impact of air velocity on system performance; cooling efficiency, cooling capacity and COP parameters should also be investigated. These analyses are presented in the following sections of the study.

Fig. 8 shows the variation of the outlet air relative humidity over 4 h testing period for the air velocities in the range of 0.1–1.2 m/s. As seen in Fig. 8, the rise in air velocity causes a reduction in relative humidity [28]. This is due to the contact time of air with material surface. As the contact time of air with the wetted surface of material is reduced with the increasing velocity, less evaporation occurs.

During the testing at 0.1 m/s air velocity, RH of the outlet air was fluctuated around 60%. On the other hand RH for the first two hours at 0.3 m/s remained nearly constant at around RH of 50% whilst it increased to 55% in the following period due to the slight rise in ambient humidity. This was followed by a uniform increase of 12% after 120 min–180 min at the highest RH of 55%. For 0.6 m/s and 0.9 m/s, the outlet RH's were remained nearly stable at around 41% and 25%, respectively.

3.2. The effect of air velocity on cooling efficiency and cooling capacity

The cooling efficiency is the most crucial parameter for identifying the potential of an evaporative cooling material. In Fig. 9, the variation in cooling efficiency is shown for different air velocities. The inlet air temperature varied between 35 and 36 °C over the four hours testing and the average highest cooling efficiency was obtained as 62% at 0.1 m/s air velocity, corresponding to a cooling capacity of 96 W.

According to the testing results, an inversely proportional relation was found between the cooling efficiency and air velocity, which is in accordance with the literature [39]. For the variation of air velocity in the range of 1.2 → 0.1 m/s, cooling efficiency was calculated between 20% → 71%. This is due to the reduced contact time between air and wet evaporation pad (eucalyptus fibre) which results with limited heat and mass transfer. The average cooling

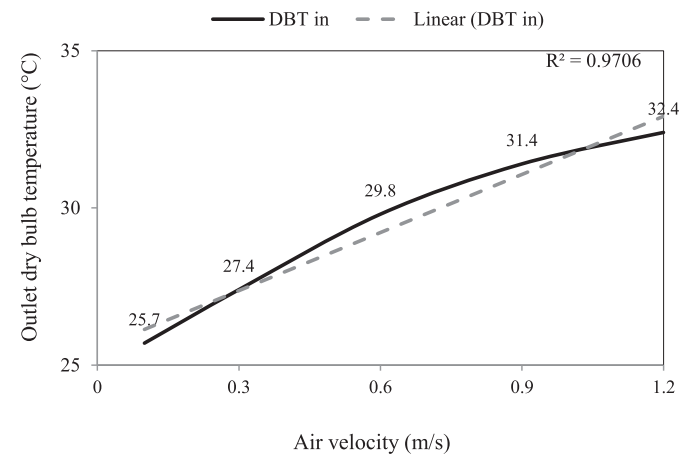


Fig. 7. The correlation between outlet dry bulb temperature and air velocity.

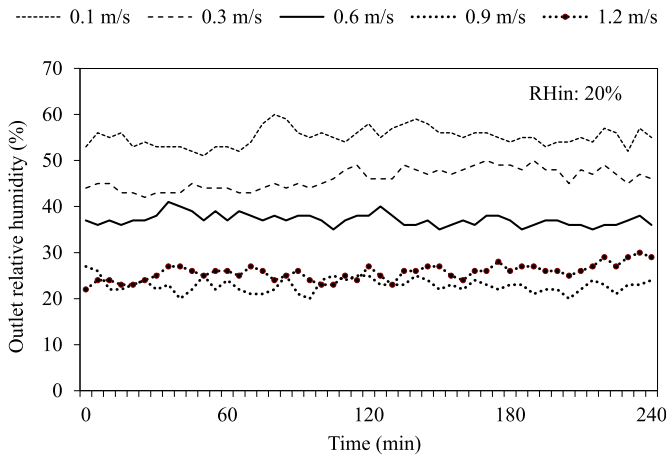


Fig. 8. Effect of air velocity on outlet relative humidity.

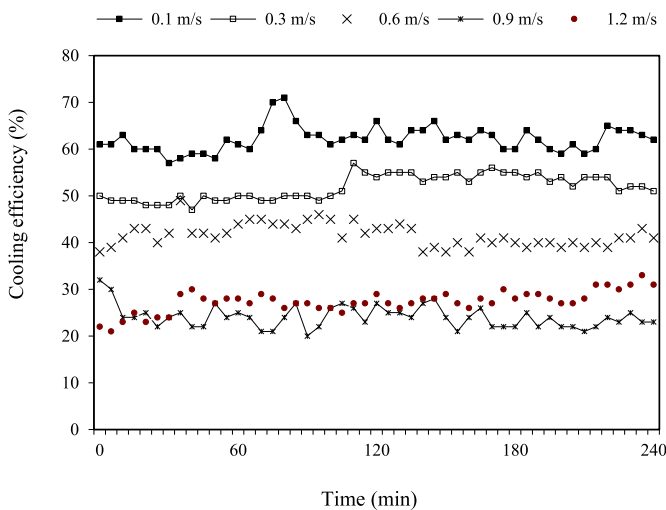


Fig. 9. Effect of different air velocities on cooling efficiency.

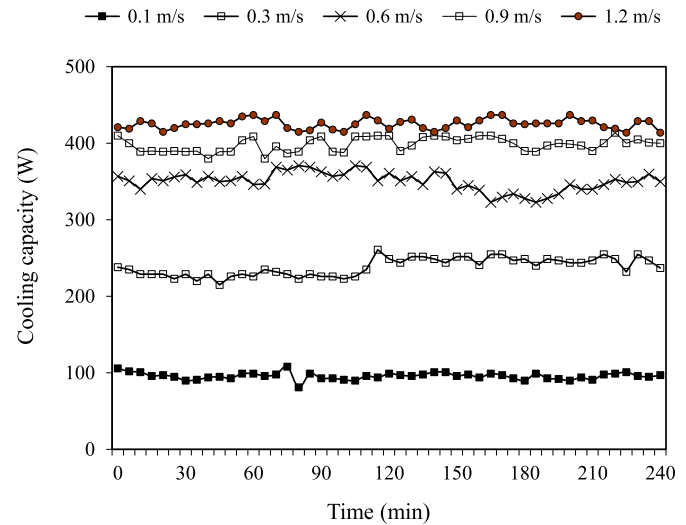


Fig. 10. Cooling capacity at 0.1–1.2 m/s.

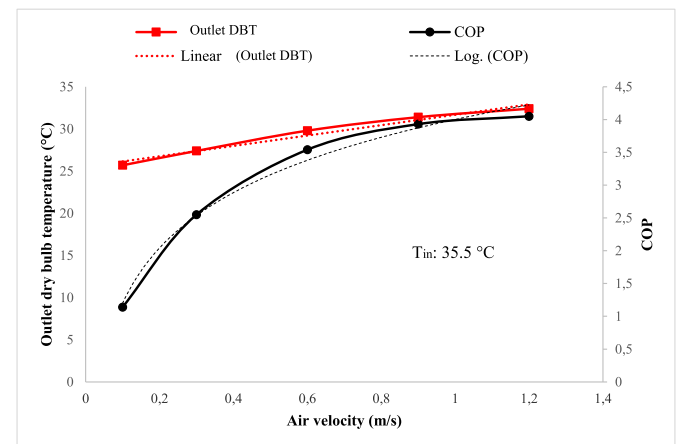


Fig. 11. Correlation of outlet dry bulb temperature and COP ($T_{in} = 35.5\text{ }^{\circ}\text{C}$).

efficiency for 0.1 m/s, 0.3 m/s, 0.6, 0.9 and 1.2 m/s air velocities were 62%, 52%, 42%, 24% and 27% respectively.

The cooling capacity (CC) of material is crucial to measure the release of heat energy during the evaporative cooling process. The variation of CC versus air velocity for meshed eucalyptus fibres is represented in Fig. 10. The figure shows that CC was raised with the increasing air velocity. This is due to the increasing evaporation rate of water at higher air velocity levels. In addition to this, cooling capacity is inversely proportional to cooling efficiency [40]. The average CC was calculated as 96 W, 239 W, 350 W, 404 W and 429 W for air velocities of 0.1, 0.3, 0.6, 0.9 and 1.2 m/s, respectively.

3.3. The effect of air velocity on COP

The correlation between outlet dry bulb temperature and air velocity and the correlation between COP and air velocity were shown in Fig. 11. As seen, temperature difference is inversely proportional with the air velocity. Despite the temperature difference gets lower with the increasing air velocity, the rate of the CC to the consumed power (fan + pump) increases. As a result, COP shows an increasing trend.

In addition to this, there is a second order correlation between air velocity and COP. As seen from the same figure, there is a sharp

increase in COP (1.2–3.5) for the change of air speed in the range of 0–0.6 m/s. However, the variation of COP becomes gradual at higher air speeds (0.6–1.2 m/s). This condition demonstrates that air speed >0.6 m/s should be used in order to obtain a high evaporative cooling performance.

Fig. 11 illustrates that the COP value was obtained at 1.2 m/s air velocity with 4.05 and it dropped to 1.14 at 0.1 m/s air velocity. In accordance, evaporation rate showed a decreasing trend in the range of 0.55 → 0.049 gr/s with the drop in air velocity. This condition demonstrates the impact of water evaporation rate on cooling COP.

Although evaporation rate and COP values were higher at 1.2 m/s air velocity, the cooling efficiency was the lowest (24%) for the eucalyptus fibre test sample utilized in the testing rig. It could be concluded that, such a small size (2 cm thickness) eucalyptus fibre is not appropriate material for evaporative cooling system at high air velocities.

It can also be concluded that COP value and cooling capacity are increased with the increase of the velocity of air up to a certain value (~0.9 m/s). Since COP is also the function of fan power, at higher velocity levels (>0.9 m/s) COP shows a decreasing trend resulting with lower evaporative cooling performance.

3.4. The effect of air velocity on evaporation rate

The trend of evaporation rate (ER) for different air velocities is shown in Fig. 12. As seen in the graph, the maximum evaporation rate of 0.55 gr/s was obtained at 1.2 m/s and it showed a gradual drop with the reduced air velocity. At 0.1 m/s, ER was ~10 times lower than the ER at 1.2 m/s. This condition demonstrates that the ER is directly proportional with the air velocity and should be optimized during the system operation depending on the cooling demand [41].

It can be concluded that eucalyptus fibres at lower air velocity shows better performance in terms of cooling efficiency compared to higher air velocity, in accordance with the literature data. The values for appropriate air velocity were 0.1 and 0.3 m/s with the highest cooling efficiency at 71 and 57% respectively. The cooling efficiency results for 0.9 and 1.2 m/s were in close approximation with an average in the range of 24–18%. The highest cooling COP values were obtained with the air velocity of 0.6 m/s, 0.9 m/s and 1.2 m/s as 3.54, 3.93 and 4.05, respectively.

Although it is obvious that the cooling efficiency at 0.6 m/s is not as high as the values at 0.1 and 0.3 m/s air velocities, COP value at that velocity was higher (3.54). The water consumption at 0.6 m/s air velocity was also lower (0.084 kg/h) than the water consumption at 0.9 and 1.2 m/s while providing higher average cooling efficiency of 42%. For that reason, it could be concluded that, in terms of cooling COP, 0.6 m/s is an optimal air velocity for the tested evaporative cooling system with the eucalyptus fibres.

3.5. The effect of air velocity on specific cooling capacity

As specific cooling capacity (SCC) is the ratio of cooling capacity to ER, it represents the cooling performance of material according to different air velocities. In other words, the specific cooling capacity is the amount of cooling capacity obtained per evaporated kg of water.

As seen in Fig. 13, specific cooling capacity is dropped with the increase of the air velocity. According to the test results provided in Fig. 13, the drop in SCC is minimal (0.54 → 0.49 kWh/kg) for the range of air velocities 0.1 → 0.6, whereas a sharp drop (0.49 → 0.26 kWh/kg) is observed for the air velocities between 0.6 → 1.2 m/s. This finding shows that system operation is most efficient at ~0.6 m/s, when both COP and SCC parameters are considered.

CC and ER are two factors that affect the specific cooling capacity. Therefore, they are both the function of velocity and they are both directly proportional to each other. But the rate of the increase of ER

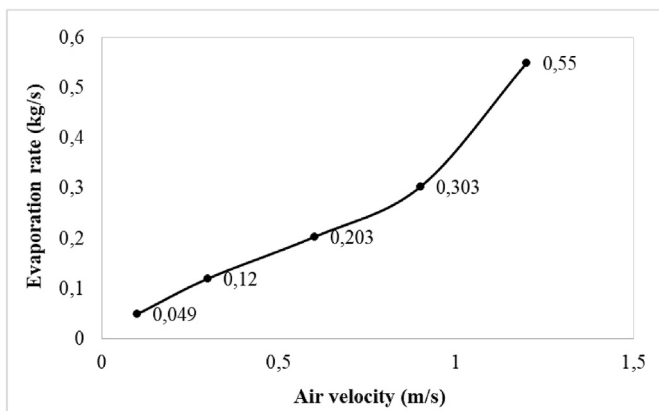


Fig. 12. Evaporation rate trends at 0.1–1.2 m/s.

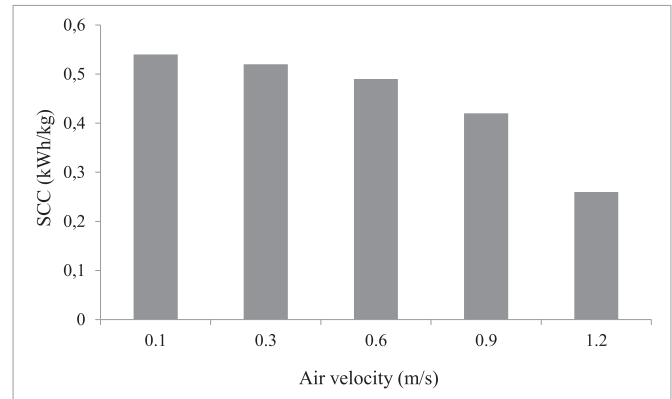


Fig. 13. Specific cooling capacity trends at 0.1–1.2 m/s.

is greater than the CC with the increase of the velocity. Therefore, SCC gets lower at high air velocity. According to this, the velocity of the air should be kept lower in order to use water in more effective manner and to minimize water consumption.

3.6. Comparison of testing result for eucalyptus fibres and system optimization

In this part of the study, the performance of eucalyptus fibres is compared in terms of SCC, CC, COP, mass flow rate and ER. Moreover, the optimum design conditions are indicated in the graph. The summary of the testing results of eucalyptus fibres are shown in Table 4.

As seen in Fig. 14, the CC gets higher with the increase of the mass flow rate since these two parameters are directly proportional to each other. In contrast, SCC was dropped with the increase of the mass flow rate. This indicates that, at higher air velocities more water is evaporated during the process and thus more water vapour is added to the air. As a result, water consumption rate becomes higher for the same cooling generated. This is a significant factor especially for regions where there is water scarcity.

As seen from the Fig. 14, SCC and CC are indirectly proportional to each other during the evaporative cooler operation. It is desirable to have both high SCC and high CC. Therefore, the intersection point can be considered as optimum operational conditions for the use of eucalyptus fibres as evaporative cooling pad.

In contrast to SCC, cooling COP showed an increasing trend with the rise of mass flow rate (See: Fig. 15). COP sharply increased up to mass flow rate of ~0.06 kg/s and then, it showed a gradual change. On the other hand specific cooling capacity was dramatically decreased for the change of mass flow rate in the range of 0.0096–0.058 kg/s and the drop became more gradual at higher mass flow rates. The intersection point of two curves gives the optimum design conditions at ~0.06 kg/s as seen Fig. 15.

The variations of CC and SCC versus ER for eucalyptus fibres are represented in Fig. 16. As indicated in the graph, the cooling capacity increases linearly until 0.2 gr/s evaporation rate.

This is due to the increase of the mass flow rate and thus the convection rate. After that point, the increase in cooling capacity falls as the effect of the evaporation on air temperature difference is minimal due to the reason that the air humidity is close to saturation point. According to the graph, there is also an indirect relation between CC and SCC. This is because that the ratio of the increase of ER is higher than the CC with the increasing mass flow rate.

The intersection point of two curves indicates the optimum design condition of the eucalyptus fibres for evaporative cooling pad as given in Table 5.

Table 4
Eucalyptus fibre based evaporative cooler performance at different air velocities.

Velocity (m/s)	Mass flow rate (kg/s)	Evaporation rate (gr/s)	SCC (kWh/kg)	Cooling capacity (kW)	COP
1.2	0.115	0.55	0.26	0.518	4.05
0.9	0.0864	0.303	0.42	0.458	3.93
0.6	0.058	0.203	0.49	0.363	3.54
0.3	0.029	0.12	0.52	0.226	2.55
0.1	0.0096	0.049	0.54	0.096	1.14

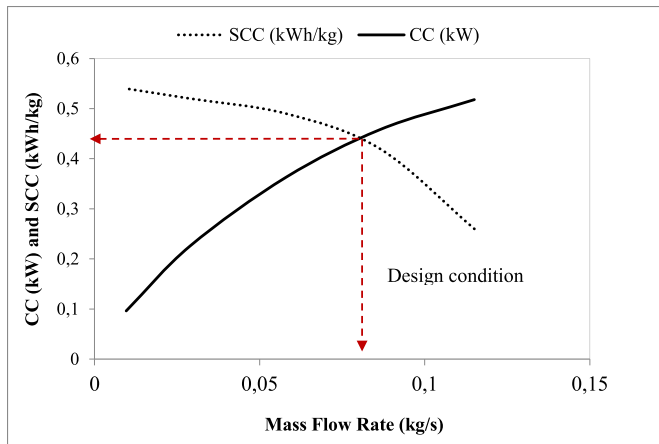


Fig. 14. Combined effects of SCC and CC at different mass flow rates.

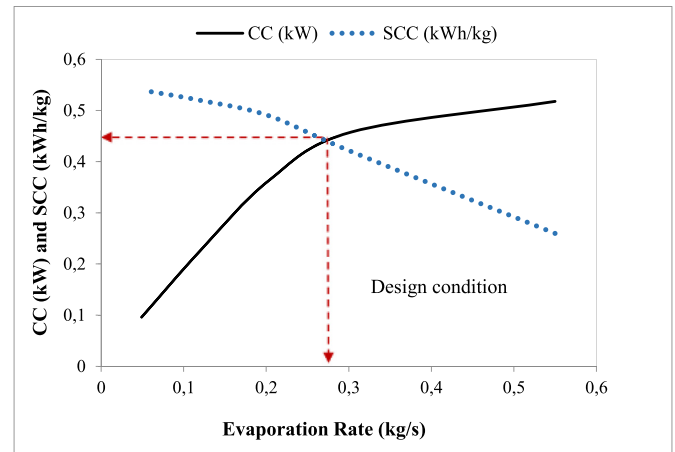


Fig. 16. CC and SCC at different evaporation rates.

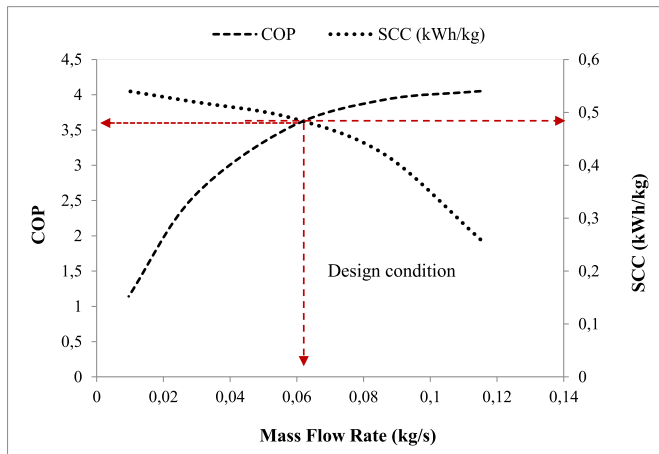


Fig. 15. Combined effects of COP and SCC at different mass flow rates.

Table 5
Optimum design conditions of evaporative cooler using eucalyptus fibres.

Parameter	Design value
Mass flow rate, \dot{m}	0.06–0.08 kg/s
Specific cooling capacity, SCC	0.44–0.48
Coefficient of performance, COP	3.65
Cooling Capacity, CC	0.44 kW
Air velocity, ϑ	0.6–0.9 m/s
Evaporation rate, ER	0.27 gr/s

structure to combine lighting, heating together with cooling purpose and the approach could be named as *combined wall*.

As sun is coming from the south in northern hemisphere, the evaporative cooling system can be integrated into wall facing to the sun. Regarding the prevailing wind direction, the system can be directed towards the strongest wind. Thus, the integrated system can be used in facade facing strong wind and sun to provide both shading, lighting and cooling effect.

One side of combined wall where large openings with shading elements are located, allows the sun comes in from the openings facing south-west providing clear visual sights, penetration of sunlight and daylight (Fig. 17).

5. Conclusion

According to the study results, it can be concluded that the eucalyptus fibres at low air velocity, provides better performance in terms of cooling efficiency, in accordance with the literature data. The air velocities of 0.1 and 0.3 m/s provided the highest cooling efficiencies as 71 and 57% respectively for the test sample. The cooling efficiency results for 0.9 and 1.2 m/s were in close approximation with the averages of 24% and 18% respectively. In contrast, the highest COP value is obtained at air velocities of 0.9 and 1.2 m/s, with 3.93 and 4.05 respectively.

In the presented study a new organic material with good water holding capacity has investigated for evaporative cooling applications. Study results showed that the eucalyptus fibres could be an alternative material to be used in future evaporative cooling systems. Currently celdek pads, cellulosic pads, aspen pad, rigid medium pad ... etc., are mostly used. Despite these materials are efficient they are expensive due to the fabrication and processing costs. On the other hand eucalyptus fibres is a natural, easy to find and abundant in most locations. Therefore it could be a low cost opportunity to be utilized in less developed hot countries.

4. Potential application of eucalyptus fibre based passive evaporative cooling system

The evaporative cooling system can be integrated into a wall

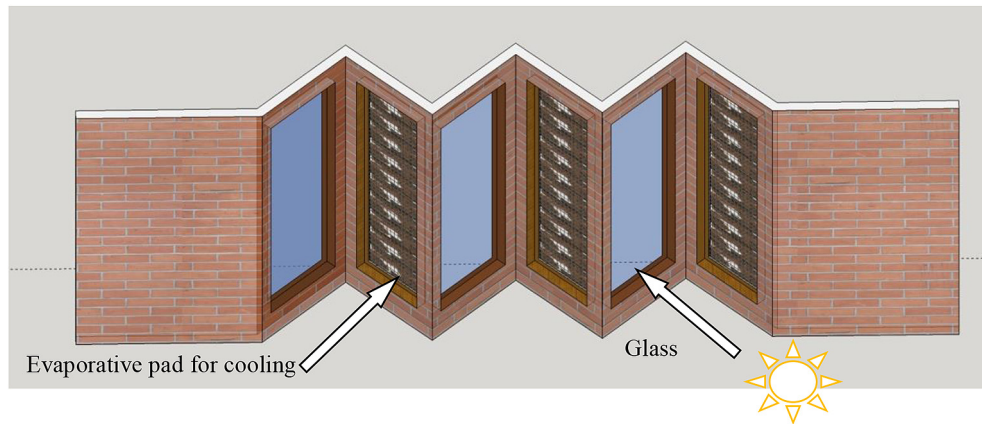


Fig. 17. Evaporative cooling system facing sun and strong wind.

Despite the cooling efficiency shows a decreasing trend with the increase in the air velocity, COP cooling gets higher at higher air velocities. SCC also showed a sharp increase with the increase of the air velocity up to 0.6 m/s. At higher velocities, SCC became steadier. The investigated evaporative cooling system provided a maximum COP cooling of 4.05. Considering all evaluated operational parameters, optimal operating air velocity for the eucalyptus fibres for the investigated unit was found ~0.6 m/s.

In this study, a new evaporative cooling pad using eucalyptus fibres is presented. It is shown that this material provides good cooling efficiency and high cooling capacity per kg of water consumption. Due to the advantages of being low cost, light in weight, abundant and environmentally friendly also having high water holding capacity and long life span, eucalyptus fibres can be an alternative material that can be used as evaporation pad in evaporative cooling systems.

The application of eucalyptus fibres can be improved by compressing the material inside of the meshed structure in order to prevent dropping of the fibres in the fabrication process. Besides, eucalyptus fibres could be used in building integrated passive evaporative cooling applications by utilizing natural wind for providing comfort especially in hot and dry climates.

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